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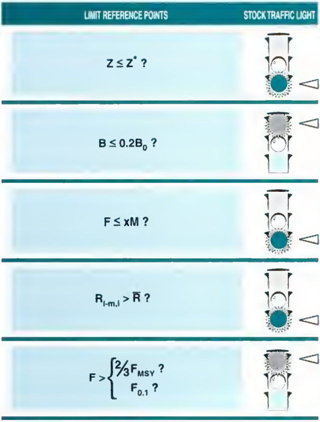
A short review of precautionary reference points and some proposals for their use in data-poor situations



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John Caddy
FAO Fisheries Department

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PREPARATION OF THIS DOCUMENT

The present document was prepared originally for a Workshop on Precaution Limit Reference Points for Highly Migratory Fish Stocks in the Western and Central Pacific, organized by the Secretariat to the Pacific Community and held in Honolulu, Hawaii, USA, on 28 and 29 May 1998. It should be regarded as a follow-up and supplement to *FAO Fisheries Technical Paper* No. 347, Reference Points for Fisheries Management, by J.F Caddy and R. Mahon, and concentrates particularly on the use of reference points in the management of fisheries where the long-time series or age-structured data sources required to use reference points are not available.

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ABSTRACT

The paper briefly summarizes the recent development and use of reference points for fisheries management and how they are currently being used to contribute to precautionary fisheries management. This implies the incorporation of reference points into 'Harvest Control Laws', which form the basis for management action but need to be reconciled through discussion and negotiation between managers and fishers and the fishing industry, since the 'risk' that a particular fishing strategy will be precautionary depends on the overall performance of the fishery as a system and not just on the precision of the reference point itself. Limit Reference Points are only one component of a precautionary management system; precision in formulating reference points as part of a fisheries control law will be ineffective in the absence of either industry's agreement to act when the limit reference points are approached or exceeded or prompt and effective surveillance to detect infringements.

A short review of reference points of actual or potential value will mainly look at those that could be of particular use for developing countries' fisheries and shellfish resources, or oceanic resources such as tuna, where lack of data on age structure and recruitment makes application of some of the conventional approaches used in north-boreal shelf fisheries uncertain. One suggestion that will be made is to consider how multiple reference points might be used based on different criteria.

The North Atlantic area is taken as an example of an area where considerable progress has already been made in defining reference points, but emphasis within the Northwest Atlantic Fisheries Organization (NAFO) and the International Council for the Exploration of the Sea (ICES) has largely been on defining RPs dependent on the existence of time series of age-structured data, a data-rich situation unlikely to currently apply to many tuna stocks and tropical fisheries. Where data is scarce, precaution is even more necessary, but reference points may have to be partly empirical, and emphasis is placed on describing a number of options to be explored further through simulation and, later, practical trials. Attention is given to different ways in which they could be combined in control laws within a fisheries management system.

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INTRODUCTION

The last few years have seen a major proliferation of action on the formulation of reference points to achieve precautionary fishery management goals, following the technical Working Group of the Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks that met in 1994-95 (Annex 2 of that Report describes this requirement; UN 1995). This working group based its efforts on two FAO Fisheries Circulars: one on precaution, the other on reference points (FAO, 1995a, b). The latter document, later revised and extended (Caddy and Mahon, 1995), put forward the concept of Limit Reference Points (LRPs) as one practical way of defining the limits to exploitation of a stock. Following this, recent work has distinguished Target Reference Points (TRPs) from Limit Reference Points (LRPs), but their relative role in the management process still remains somewhat unclear, and divergences of approach are evident, in which more than two types of reference points appear to be emerging.

What is most of concern with respect to the way the LRP concept has developed since the UN Conference and its base documents is that most current work on LRPs is aimed at the definition of reference points, with relatively less emphasis or experience on how efficiently they will perform in a functioning management system. As noted in an earlier communication (Caddy, 1997), this may require significant changes in the way that management bodies function but will also require a systems approach in which industry, managers and scientists discuss their respective roles, particularly in defining the risk to the resource of implementing a given management measure.

It may be worth recalling here that previous management approaches based on target reference points alone had proved vulnerable to overfishing once a TRP had been overshot. This was partly because of the high degree of uncertainty in locating the current position of the fishery in relation to the TRP but also because recovery times after effort overshoots were often long and because mechanisms for integrating the efforts of scientists, managers and fishermen into a single responsive fisheries management system had been neglected. Often adversarial positions were adopted in the course of management decision-making that required long negotiations and inconclusive management responses before the 'fishery system' could react to downturns in resource abundance due to fishing or natural causes. In the interim, the fishery continued to overfish the stock in absence of a prenegotiated, precautionary approach to management which is integral to the new legal instruments. We may expect similar anomalies with the application of LRP-based management systems (Fig.1), unless a systems approach is agreed to by all parties.

The new paradigm whereby LRPs are defined was incorporated into the UN Agreement and is also part of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995c). Integral to this LRP approach is the concept that the fishery as a 'system' will react to the approach of the fishery to an LRP by adopting a prenegotiated response to unfavourable events. This will necessarily involve sharp reductions in fishing effort over a period sufficiently sustained for the stock to return to a healthy condition, i.e. a stock recovery strategy will have to be applied to bring it back to a spawning biomass significantly higher than that at which the LRP is established.

Defining such a recovery target involves setting a distinct biomass-based management RP. This is defined by recent international instruments as that at which "the stock can support the harvesting of an MSY without adverse impacts". This is not to imply, of course, that the MSY conditions should be the target for harvesting; to the contrary, both the FAO Code of Conduct and the UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks indicate that MSY conditions should be regarded as representing a limiting condition that should not be exceeded (for F_{MSY}) or allowed to fall below (for B_{MSY}), and MSY conditions now constitute minimum conditions for stock recovery.

Questions relating to the definition of RPs have been the source of major discussion in a number of fora, for two of which a summary of the current position is given here, mainly based on the reports of Serchuck *et al.* (1997) for NAFO and ICES (1998).

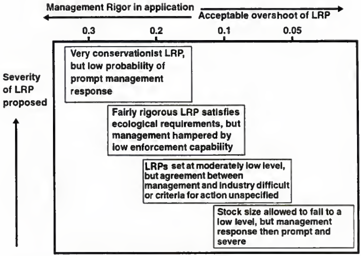

Management Rigor in application
Acceptable overshoot of LRP
0.3
0.2
0.1
0.05
Severity of LRP proposed
Very conservationist LRP, but low probability of prompt management response
Fairly rigorous LRP satisfies ecological requirements, but management hampered by low enforcement capability
LRPs set at moderately low level, but agreement between management and industry difficult or criteria for action unspecified
Stock size allowed to fall to a low level, but management response then prompt and severe

Figure 1. Illustrating the necessary linkage between precision of definition of reference points, acceptable level of overshoot and management rigour in enforcing a fishery control law based upon them.

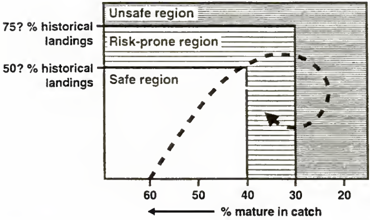


Figure 2. Example of a simple approach to 'zoning' safe and risky fishing conditions using peak or mean historical landings and percent mature fish in the catch.

SOME GENERAL CONSIDERATIONS

The concept of reference points might imply to those unfamiliar with the practicalities of assessment science that managers know exactly where the fishery is in relation to them, and whether they are in a 'safe'or 'unsafe' condition. This is of course not so, given coefficients of variation for most relevant variables even in well-documented fisheries of 10-30+% (Caddy and Mahon, 1995). What in effect will be required for 'precaution' is to translate reference points from deterministic values into likelihoods of the fishery finding itself in a more or less risk-prone zone (Fig.2). Before proceeding too far with refinements on RP estimation, it would be wise (Table 1) to carry out a broad review of the biological (and economic) literature in search of possible indices that could measure particularly sensitive aspects of the actual conservation situation of the resource in question (Caddy, 1998), and this has particular relevance for tunas.

Table 1. Precautionary management procedures*

A review of the biological basis for fisheries management would minimally cover:

- management procedures currently in place and their consequences
- scope of feasible management actions available for the fishery
- stock structure of the species involved
- main predator-prey relationships
- main environmental relationships as they affect recruitment and growth
- distribution of the stock with respect to the distribution of the fishery
- spawning areas
- juvenile areas and rearing areas
- migration patterns by size/age groups
- influence of density on growth and/or distribution
- variability in recruitment and its main causes
- stock-recruitment relationships
- fleet composition, the fisheries in which they are involved, their interactions and their selectivities
- robustness of various stock assessment approach (including statistical catch-at-age analysis)
- possibility of a catastrophe (e.g. what happened for these stocks in the past or for stocks with similar characteristics elsewhere).

Assessment working groups would normally either provide these reviews or be closely involved in them.

*(from Report of the Comprehensive Fishery Evaluation Working Group, ICES Headquarters, 25 June - 4 July 1997. Advisory Committee on Fishery Management, ICES CM 1997/Assess:15)

Table 2. Control Law RPs and some possible technical RPs to include in them, according to ICES and NAFO

Control Law RPs (ICES)	Possible Technical Reference Points (ICES)	Control Law RPs (NAFO)	Technical RPs: Data-rich fisheries (NAFO)	Data-moderate-to-poor fisheries (NAFO)
B_{LIM}	0.5 B_{MSY}	F_{MSY}		$0.2*B_0$
F_{LIM}	F_{MSY}, F_{CRASH}	F_{LIM}	F_{MSY}, F_{MAX}, F_{MED}	F_{MSY}, $F_{30\%}$
B_{PA}	B_{MSY}	B_{BUF}	$= B_{LIM}.\exp^{+2S}$	
F_{PA}	$F_{0.1}$, F_{MED} $= F_{MSY}.\text{axp } -2S$, $= F_{CRASH}.\exp^{-2S}$	F_{BUF}	$= F_{LIM}.\exp^{-2S}$	f(M), $0.5*F_{MSY}$
$F_{PA} = F_{ComFIE(1)}$	= MIN (F_{MSY}, F_{MED})	B_{TARGET}	£ = B_{MSY}	
$F_{PA} = F_{ComFIE(2)}$	= MIN (F_{MSY}, F_{MED}, $F_{0.1}$)	F_{TARGET}	£ = F_{BUF}	

From Table 2 and Figures 3 and 4 some differences, but also many similarities, emerge between the approaches of ICES and NAFO: the first reflects the purely advisory role of ICES (no targets for fishing are suggested), while a slightly more precautionary approach is adopted by NAFO in which different 'zones' of the control law diagram (Fig.4) correspond to different fishing strategies. Also, fishing below F_{BUF} is prohibited by NAFO but not specified in the control law by ICES. A further note is that the F_{TARGET} and B_{TARGET} criteria of ICES are mainly intended for stock recovery strategies, although there is not a particularly clear distinction (at least to this author) between stock recovery strategies and what happens following effort cut-backs once an LRP has been infringed. Apart from these differences, we can say that, in practice, F_{BUF} and F_{PA} are LRPs but are also likely to be treated as targets if it is decided to exploit the stock to its maximum, so that, for most purposes,

$$\text{MAX}(F_{TARGET}) = F_{BUF}(\text{NAFO}) = F_{PA}(\text{ICES})$$

The value of $\underline{S}$ in the above equations is left undefined, and the effects of different values are apparently established by simulating exploited life histories, suitable values chosen being such that, for example, there is a 50% chance of a stock recovering to MSY conditions in (e.g.) 10 years.

In elaboration of the original UN scheme which implied a single TRP/LRP pair, in the North Atlantic a second precautionary reference point, known as F_{PA}, (F precautionary) is incorporated. This is the upper limit for fishing mortality rate and is set significantly lower than the F-based LRP, with the intention that fishing effort be progressively reduced once this point is reached and biomass starts to decline (Figs 3 and 4). A comparable RP framed in terms of biomass is B_{PA}, which has the role of ensuring that the fishery stays in the zone above an LRP established in terms of spawning biomass.

Within NAFO, B_{BUF} plays a comparable role as the 'first line of defense', being the biomass level that once dropped below triggers immediate action, in this case to slow exploitation, such that there is a low probability that B_{LIM} will not be reached. Both 'PA' and 'BUF' suffixes distinguish not so much the way the reference point is calculated or defined but its role within a harvest control rule or law. As noted above, these levels of F and B can either be regarded as LRPs themselves in the sense used in FAO (1995b) or can be regarded as extreme values for TRPs.

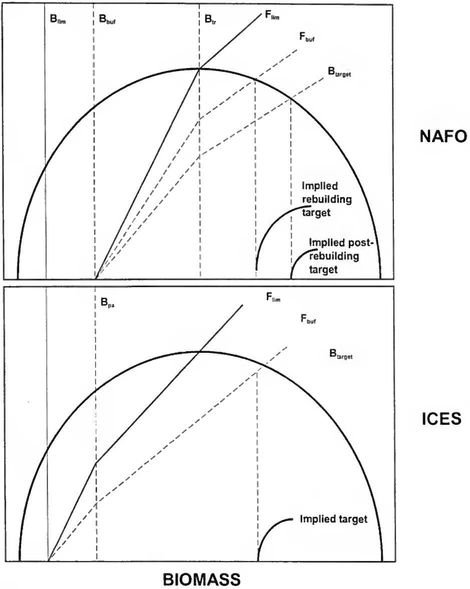


Figure 3. Equilibrium yield as a function of biomass with harvest control laws suggested by NAFO (*upper*) and ICES (*lower*) (from ICES, 1997).

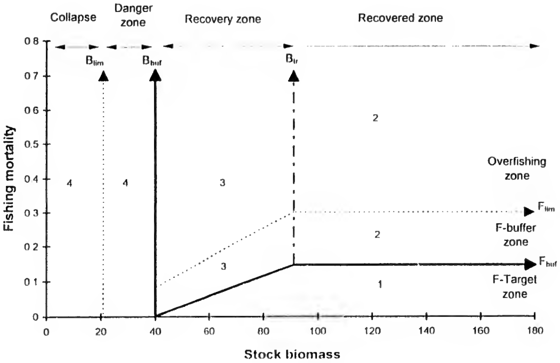


Figure 4. 'Zoned' approach to a harvest control law (from NAFO reports).

One can deduce from the need to formulate 'BUF' and 'PA' RPs that the actual 'extreme-value' LRPs chosen by ICES and NAFO have been set at such a low, critical level of biomass that one would expect a serious threat of immediate stock collapse if they were attained or even approached. This would be the case for F_{CRASH} for example, which is defined as the point at which yield declines to zero using age-structured data in the Shepherd production model (Shepherd, 1982; Fig.5). One may question whether an alternative approach might be equally effective, namely establishing one set of LRPs at a higher level of stock size but allowing a slightly higher but controlled probability of overshoot. This was the possibility discussed by Caddy and McGarvey (1996), assuming only a single pair of TRP/LRPs.

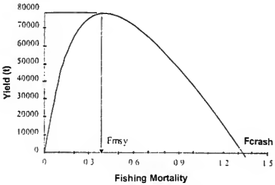


Figure 5. Equilibrium yield as a function of fishing mortality determined from an age-structured production model (after Shepherd, 1982)

The NAFO approach to precautionary management can be summarized by the Control Law:

1. Ensure that: SSB $>> B_{BUF} > B_{LIM}$

2. Maintain: $F_{TARGET} <= F_{BUF} < F_{LIM}$

(See Serchuck *et al.*, 1997).

This scheme in effect shows the transition from a simple pair of LRP/TRPs towards a Harvest Control Law, but the approach still depends on effectively being able to judge where the fishery is in relation to a given RP.

The fact of suggesting an RP such as $F_{ComFIE(2)}$, which considers a 'basket' of LRPs, and responses to the first of these to be infringed, illustrates that, with current uncertainties, it might be better to not rely unduly on only one estimator if a real degree of precaution is required under uncertain conditions. This was also the motive for suggesting the 'traffic-light' approach described later in the document.

The comparable control law proposed by the ICES Comprehensive Fisheries Evaluation (ComFIE) Report (ComFIE, 1997) is given in three steps (Fig.3), starting from low and moving to high levels of exploitation:

1. $F = F_{0.1}$ for $B > B_{PA}$

2. $F = F_{0.1} * (B - B_{LIM})/(B_{PA} - B_{LIM})$ for $B_{LIM} < B <= B_{PA}$

3. $F -> 0$ for $B < B_{LIM}$

(Here B_{LIM} is defined as $0.5\ B_{MSY}$ and $B_{PA} = B_{MSY}$)

THE ROLE OF RPs AND HARVEST LAWS IN MANAGEMENT

One fundamental aspect here that is left out of much of the technical documentation on RPs is that in both the Code and UN Agreement, and also emphasized in the guidelines for applying the precautionary approach (FAO, 1995c), it is understood that reference points are only relevant if placed in their management context as part of a Fisheries Control Law that must include industry and management to be effective and must take into account risk at all levels of implementation of a Control Law (Table 3). This requires cooperation to include some or all of the following elements. Each partner in the management system needs to play a coordinated role, as illustrated in simplistic form by the following table.

Table 3. Relative roles of fishery scientists, managers and the fishing industry in management by Reference Point/Control Law

Scientists	Management	Industry
- Define options for safe targets for exploitation (TRPs) and how to measure them - Estimate current size of stocks and reproductive potential	Consider how to monitor landings, expenditure of fishing effort, changes in fishing power and area/season of fishing	Provide information on landings, biological data and areas/times as condition of licensing
Define upper limits for harvest/exploitation rate/ surviving biomass which ensures adequate spawning	Consider feasibility of reducing fishing effort drastically when stock is depleted; develop recovery plans	Negotiate with management on actions to be taken when stock reaches LRPs
Suggest options for decision rules within which LRPs and TRPs will play a key role	Agree on a decision rule and on TRPs and LRPs and consider their implications for MCS and for stock recovery strategies as needed	Negotiate with management on practicalities of the fishermen's response when key points in decision rule and LRPs are reached

It is clear that TRPs and LRPs alone do not lead to a responsible or precautionary management response, and Figure 1 illustrates that a high degree of rigour is appropriate in setting LRPs only if the management response is designed to be rapid and effective in controlling potential overfishing. Reference points can only be effective if appropriate management responses (and, by the same token, agreement with the fishing industry) are prenegotiated and effectively implemented. If this is not the case, what may be needed are a number of empirical, but easily understood, indicators of potentially dangerous conditions, which can be phrased as easily measured quantities, directly relevant to the fishery in question.

Relevant in this respect is that, within ICES, the precautionary basis for advice given to ACFM will be that, for a given stock, "the probability of exceeding the limit reference point will be no greater than 5% in any given year" (Serchuk *et al.*, 1997). The implication of this, of course, given that current data from the fishery (e.g. catches, survey biomasses) have an intrinsic coefficient of variance probably of the order of 20-30%, is that, in order to rigorously avoid the zone close to the LRP, the TRP must be set at a low level, or one or more other controls must be in place to detect and respond to declines in stock levels even before the LRP is reached.

One issue that comes out of recent intensive studies by ICES, NAFO and other organizations is that the search for practical limit reference points has generated an unprecedented amount of new research on how to set the limits to exploitation. The danger, however, is that this search become disconnected from the management process as a whole and that the systems view of a fishery be lost. Views were even expressed in the relevant scientific reports that the precautionary approach is not a matter of concern to scientists but solely relevant to managers. Certainly, scientists cannot preempt the role of managers and should not bias their analyses in the search for results that are more 'safe' for the fishery as a whole. At the same time, the fishery is an objective system, and someone needs to consider its performance in toto, and this is a legitimate role for systems scientists in cooperation with the other players or stockholders. In doing this, it will also be necessary for scientists to calculate the risks of the overall management system not meeting its goals, given a series of likely eventualities. Defining LRPs alone will not achieve this 'Systems Science Goal'.

With this in mind, it may be worth illustrating several alternative ways in which an LRP-based system might operate. Figures 3 and 4 show decision rules adopted by ICES and NAFO and Table 4 gives some of the reference points proposed for inclusion in these rules. One might suppose that following procedures similar to those proposed by the IWC in the late 1980s that, if the fishery and resource are well understood, such 'harvest- control laws' could be elaborated in even more detail, negotiated with industry and set to function largely independently of annual assessments in the form of 'fishery management procedures'. Such an approach has been described for South African fisheries (e.g. Butterworth *et al.*, 1997); the 'traffic-light' approach described later offers a different approach to the same problem.

Table 4. Some biological reference points*

F_{01}: fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of its value near the origin.

F_{max}: fishing mortality rate which corresponds to the maximum yield per recruit as a function of fishing mortality.

F_{low}: fishing mortality rate on an equilibrium population with a SSB/R equal to the inverse of the 10th percentile of the observed R/SSB.

F_{med}: fishing mortality rate on an equilibrium population with a SSB/R equal to the inverse of the median observed R/SSB.

F_{high}: fishing mortality rate on an equilibrium population with a SSB/R equal to the inverse of the 90th percentile of the observed R/SSB.

$F_{x\%}$: fishing mortality rate on an equilibrium population with a SSB/R of the SSB/R for the corresponding unfished population.

B_{MSY}: biomass corresponding to maximum sustainable yield as estimated from a production model.

F_{MSY}: fishing mortality rate which corresponds to the maximum sustainable yield as estimated by a production model.

F_{crash}: fishing mortality which corresponds to the upper intersection of the yield and fishing mortality relationship with the fishing mortality axis as estimated by an F-based production model.

F_{LOSS}: the replacement line corresponding to the Lowest Observed Spawning Stock (LOSS).

$B_{50\%\ R}$: the level of spawning stock at which average recruitment is one half of the maximum of the underlying stock-recruitment relationships.

$B_{90\%\ R,\ 90\%\ Surv}$: level of spawning stock corresponding to the intersection of the 90th percentile of observed survival rate (R/S) and the 90th percentile of the recruitment observations.

Estimates of these quantities may be conditional on the stock-recruitment relationships assumed.

*(from Report of the Comprehensive Fishery Evaluation Working Group, ICES Headquarters, 25 June - 4 July 1997. Advisory Committee on Fishery Management, ICES CM 1997/Assess:15)

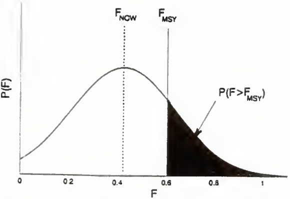


Figure 6. Excerpt from Caddy and McGarvay (1966) assuming F_{MSY} as the LPR. *Above:* Illustrating variance in the current best estimate of fishing mortality, F_{NOW}. *Below:* Corresponding levels of $F_{(TRP)}$ for different values of the c.v. and the agreed overshoot of $F_{(LRP)}$.

Estimates of target fishing mortality (F_{NOW}) in relation to (a) the risk (probability P) that current F exceeds the limit reference point F_{MSY} = 0.6 (fishing mortality at maximum sustainable yield) and (b) the coefficient of variation[a] of F (CV_F), calculated for normal and log-normal distributions of uncertainty in F

P ($F_{NOW} > F_{MSY}$)	[a]CV_F				
	0.05	0.10	0.25	0.50	1.00
	Normal distribution of uncertainty in F				
30%	0.58	0.57	0.53	0.48	0.39
20%	0.55	0.55	0.50	0.42	0.33
10%	0.53	0.53	0.45	0.37	0.26
5%	0.52	0.52	0.43	0.33	[b]-0.04
	Lognormal distribution of uncertainty in F				
30%	0.58	0.57	0.53	0.48	0.39
20%	0.58	0.55	0.50	0.42	0.33
10%	0.56	0.53	0.45	0.37	0.26
5%	0.55	0.51	0.40	0.28	0.15

[a] CV_F = SD of the normal or lognormal distribution of F)/(mean of the respective distribution), or σ/F_{NOW}

[b] Predicted target F-values with normal distributions of uncertainty in F are in error and diverge from those predicted by the lognormal distribution but only when uncertainty is high and acceptable risk of mortality overshoot (P) is very low.

As noted, two categories of RPs are now defined: the reference point may refer to a feature of the underlying model providing it (e.g. F_{MSY}, $F_{0.1}$, F_{CRASH}, etc.), which are referred to in Table 2 as 'technical' reference points, or the RP 'acronym' may simply refer to the role of the reference point in the decision rule adopted (e.g. F_{PA}, B_{BUF}, F_{LIM}). These may be defined in terms of one or more of the above model-based RPs or be based on other empirical criteria that are of importance to the fishery in question.

What is clear from examination of recent ICES and NAFO reports is that almost all RPs currently in use are based in some way or other on the availability of age-structured data and on information on stock and recruitment accumulated over a significant period of time. Where production models are used offering estimates of MSY or F_{CRASH}, for ICES these are largely derived from the Shephard (1982) model which creates a general production function from stock-recruit data.

This dependence on stock recruit information was the problem facing the NAFO meeting in March 1998 since for many NAFO stocks of fish or invertebrates age data and time series are not readily available. In a sense, then, these NAFO stocks (such as cephalopods and shrimp) face some of the same problems as most tuna fisheries and almost all developing country fisheries in defining precautionary reference points. For these, one may have to seek other less rigorous approaches to setting reference points. This is where it is again essential to consider how reference points are going to be used by managers and understood by fishermen. In other words, a highly technical RP or control law will be difficult to explain to industry and will still need to accumulate practical experience 'on the grounds', while a less precise or 'empirical' RP may be effective if it is understood and receives consensus from industry and still leads to reproducible results.

It is even possible that relatively arbitrary value(s) may be adopted for RPs which attempt to reproduce situations similar to those remembered by the industry in earlier favourable years in the fishery (e.g. B_{1965} or B_{1970}, or values for RPs may be used that appear to be precautionary from experience in this fishery or elsewhere. In fact, it can be noted that the setting of 'pairs' of LRPs and TRPs using formulations such as $[F_{PA} = F_{LIM}.\mathrm{exp}\text{-}2^{S}]$ in Table 2 is an arbitrary but necessary procedure; the 'distance' between the TRP and LRP depends on the value of S̲ which so far has not usually been defined but is typically taken as 0.2-0.3 (ICES sources).

The point is that, however defined, RPs will need to be subject to some 'tuning' as part of a fishery management system and will probably have to be modified in light of practical experience. Relevant experience here was gained in South African fisheries, where, even though in an early version of a management system, a prenegotiated management response had been agreed to with industry, but experience soon led to its modification in the light of its application.

It is of particular interest to note that, where there is inadequate data for establishing a harvest control law, it may be still possible to set a single LRP that corresponds to serious but not catastrophic conditions and then pick a TRP based on estimates of variance and probability of overshoot. Such an approach was suggested by Caddy and McGarvey (1996) and may provide a useful tool for guessing a suitable value for a TRP, given a pre-established LRP. Although, as noted by Caddy and McGarvey (1996), the variance of fishing mortality is difficult to estimate, reasonable orders of magnitude can usually be guessed at by those familiar with a fishery. As an example, given a value of $CV_F = 0.25$ and $F_{LIM} = 0.6$, this provides a value for $F_{NOW} = F_{PA}$ of the order of $F = 0.4\text{-}0.43$, with an acceptable probability of overshoot of 5%. A similar value could be derived from the Appendix and the table in Figure 6, from Caddy and McGarvey (1996). As noted, such an estimate requires that the risk of overshoot of the LRP acceptable to managers be also specified, a factor which is not generally taken into account in most LRP-based systems.

OBJECTIVES UNDERLYING FORMULATION OF MANAGEMENT AND REFERENCE POINTS

Three major management strategies have been described (see Caddy and Mahon, 1996), namely management for a given level of quota, for a given exploitation rate or for a pre-agreed level of spawning escapement. These have more recently been combined with threshold or limit reference point policies (e.g. Quinn *et al.*, 1990). Viewed from the perspective of precaution and the reference points involved, the first of these strategies implies of course quota control, and despite current perspective in many areas of its suitability as a limit reference point, MSY, or more precautionary 2/3 MSY, are RPs here.

The second strategy could, of course, be implemented in a straightforward fashion with control of fleet capacity and fishing power as its primary control variables, although, again, some secondary application of quotas to keep exploitation rates close to constant is usually the strategy adopted. The reference points $F_{0.1}$ (Gulland and Boerema, 1973) or, more cautiously, $F_{0.2}$ (Butterworth *et al.*, 1997) are the classical target reference points that correspond to this strategy, with some common RPs, such as F_{MAX}, potentially providing an upper limit.

The third strategy is of course a biomass-based approach, with emphasis on maintenance of spawning potential and monitoring survival of recruits. Here, stock-recruit approaches originally applied for salmon stocks on the Pacific coast of North America have been applied in North-Atlantic areas to groundfish, using either the classical Beverton and Holt or Ricker S-R relationships to define RPs such as F_{LOSS} (Table 4). Recently, the Shepherd production model, which is fitted to age structured data, is the model which is most commonly used and is employed to define truly catastrophic LRPs such as F_{CRASH} (Fig.5). Where age-structured time series are not available, SSB/R calculations yield LRPs such as $F_{\%SPR}$ as described by Clark (1991).

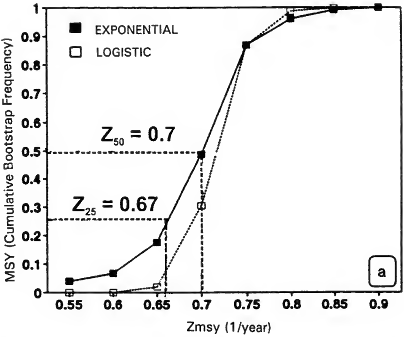


Figure 7. Bootstrap estimates of the total mortality rate at MSY (Z_{MSY}) in a logistic model expressed as cumulative values. Two percentiles, S_{25} and Z_{50}, might be candidates for a TRP/LP pair (Caddy and Defeo, 1996)

A BRIEF CLASSIFICATION OF LRPs AND THEIR APPLICABILITY IN INFORMATION-LIMITED SITUATIONS

Reference Points Based on S-R Relationships

For completeness, reference points based on availability of historical S-R data are included here and are obviously those which require the most complete data sets, consisting of time series of age-structured catches and population sizes, often supplemented by regular biomass surveys. As noted, such reference points form the main basis for LRP definition in the ICES and, to a lesser extent, NAFO areas. For example, F_{MED} (Sissenwine and Shepherd, 1987) is the fishing pressure that reduces spawning biomass of a year class over its lifetime below the corresponding value for its parents and is estimated from the slope of the line through the origin of the S-R relationship for a fishery. Others are referred to more extensively in Mace (1988), Caddy and Mahon (1995), etc., and it remains to be seen whether these are likely to have wide application for data-poor fisheries, but a brief list of common approaches to LRP formulation follows.

Reference Points Based on Y/R and SSB/R Analysis

The classical TRP for Y/R analysis is of course F_{MAX}, which again, nowadays, tends to be regarded as an LRP, with $F_{0.1}$ commonly used as the corresponding TRP, both being subject to change as a result of changes in age distribution, recruitment and selectivity changes. Hence the need for the use of $F_{0.1}$ in conjunction with an LRP. In New Zealand, if an LRP cannot be estimated from a model, it is often substituted for by the relevant value of M (see later). In South Africa, $F_{0.2}$ is frequently used and is a more restrictive exploitation rate reference point, which has been used as a target or a benchmark in a fisheries management procedure (Butterworth *et al.*, 1997).

Spawning stock biomass/recruit reference points include F_{REP}, F_{HIGH} and F_{LOW}, and these may also be subject to variability for the same reason as mentioned for $F_{0.1}$ above (as, in fact, is true for most RPs). $F_{35\%}$ or $F_{30\%}$ are two fishing rates based on previous data sets for stock and recruitment that calculation has shown will maintain SSB/R at safe levels: the latter is an RP used by the North Pacific Fishery Management Council (Hollowed and Megrey, 1993), which is believed to be roughly equivalent to about 75% of long-term MSY as long as spawning stock size does not fall below 20-60% of the unfished level (i.e. both fishing mortality and biomass need to be monitored).

Reference Points Based on Production Modelling

The classical RP (now regarded in some quarters as an LRP) is of course F_{MSY}. In the past, MSY has been the classical management target, to be probably replaced now by quotas set at lower levels of harvest pressure, such as $F_{0.1}$ or that corresponding to 2/3 MSY, (Doubleday, 1976). Although, strictly speaking, it belongs in the previous category since in the ICES area it is usually estimated by the Shepherd approach, which depends on data for fitting S-R relationships, F_{CRASH} in theory could be estimated by more conventional production modelling as the point of interception of the right-hand limb of the curve on the fishing effort axis. One may doubt whether this is a particularly safe LRP and certainly not one to be exceeded! More relevant here could be the economic benchmark referred to as the point of Bioeconomic Equilibrium, where costs equal revenues from fishing (e.g. Panayotou, 1988). This seems a logical LRP to use, especially in high-seas fisheries where costs and revenues should be relatively easily measured.

Using size compositions to arrive at simple estimates of total annual mortality rate may allow application of production models using mortality in place of fishing effort (e.g. Caddy and Defeo, 1996). These authors show that, given reasonable time series of annual data for Z_t and Y_t, it is possible to use bootstrapping to arrive at a series of estimates for a TRP such as MSY. Ranking separate estimates and plotting them cumulatively (Fig.7), the 50% quartile of the cumulative distribution of MSY estimates might make a suitable LRP, while the 25% or more cautious percentile could be a candidate for a TRP.

Reference Points Based on Survey Data

The trend in many fisheries where commercial data is uncertain or unreliable is to rely to a progressive extent on estimates of biomass coming from surveys. While this does not seem a readily available option for most tuna fisheries, a study of a longline fishery for sablefish (Ruppert *et al.*, 1985) suggests a general formula for using survey data in setting harvests under thresholds, namely

Catch in year t of age group a: $C_{at} = G_t*(s_a*N_{at} - T)$

where G_t is some function of the exploitation fraction in year t, s_a is selectivity at age, N_{at} is the number of age group a in year t, and T is the threshold population size below which harvesting ceases. Some variation of this approach may provide elements for constructing a harvest rule whose degree of precaution will depend largely on the value of G_t used. Other more complex procedures for calculating quotas based on RPs are of course part of fishery management procedures (Butterworth *et al.*, 1997), and the 'Magnusson-Stefensson feedback gain rule' is similar and is described in the following section.

Reference Points Based on Past Fishery Yields

Past yields from a fishery, under certain circumstances, can provide some rough indication of future potential, as long as independant biological indications support the continuity of the fishery at historical levels. Some ideas on this have been proposed by Pope (1983), and in New Zealand (Annala, 1993) several yield-based reference points are currently used in fisheries management. These are either developing fisheries, in which case extremely precautionary criteria are used, or are fisheries with a fairly long history of exploitation, where maximum potential yields are believed to have been reached in the past but where the stock continues to produce at close to historical levels. Maximum Constant Yield (MCY) is the "maximum constant catch that is estimated to be sustainable, with an acceptable level of risk, at all probable future levels of biomass". Recognizing that this does not take into account future catastrophes, under certain constraints it nonetheless corresponds to a relatively low level of harvest and can be regarded as a precautionary target, which could be tested by stochastic simulations incorporating likely recruitment variability.

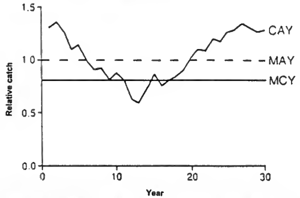


Figure 8. Relationships among Maximum Yield (MCY), Current Annual Yield (CAY) and Maximum Average Yield (MAY) (from Annala, 1993)

Current Annual Yield (CAY) is a dynamic version of MCY (Fig.8), in which a constant exploitation strategy at F_{REF} is applied. This F-based reference point is "the level of instantaneous fishing mortality which, if applied each year, would, with an acceptable level of risk, maximize the average catch from the fishery" and, again, would be established from simulation. According to Annala, CAY is calculated as:

$CAY = [F_{REF}/(F_{REF} + M)]*[1\text{-}exp - (F_{REF} + M)]*B_{BEG}$

where B_{BEG} is the stock biomass at the beginning of the fishing year.

The mean value of historical annual values of CAYs is another measure, the Maximum Average Yield (MAY) (Fig.8), which is considered to be close to MSY and is often interpreted as such by New Zealand's fishing industry (Annala, 1993).

One other useful approach to setting quotas when only commercial or survey indices are available has been referred to as the 'Magnusson-Stefensson feedback gain rule' (NAFO, 1998 draft report) and is reported as particularly useful for restoring a depleted fishery to productive condition which has been gradually declining in stock size over time. The rule is:

$$Y_t = Y_{t-1}*(1+g\ (B_{t-1} - B_{t-2})/B_{t-2})$$

where Y is catch and B is biomass (or commercial CPUE index) in year t, and g, referred to as the 'feedback gain', reflects the degree of proportionality between changes in biomass observed between the last and current year and, hence, the extent to which it will be reflected in the coming quota. Values for g of 1 and over seemed to contribute to precautionary approaches in simulations, but higher values of g were found to do so by leading to progressively more frequent closures.

Other Empirical Approaches

The concept of an RP as a 'conventional' value that is accepted by industry is one idea that may have to be considered if available data does not allow calculation of a 'scientific' or model-based index (even performance of these latter is inevitably uncertain until they have been used in a management system, for reasons mentioned earlier). One example here was the use of a spawning escapement (40% of the biomass) for squid stocks in the Falkland-Malvinas region, which was in a sense used as an LRP. Such a 'conventionalized' approach to setting LRPs appears more feasible, if one considers that, even with the best of analyses, a system of LRP-based management will depend for its feasibility on the degree of implementation (Fig.1).

A further generalization that may be useful is to consider F-based RPs in terms of the natural mortality rates that apply to a stock, since these are, after all, the natural level of risk the stock faced before fishing begins. For tunas, these values probably range from around 0.5 - 0.8+ annually for small tunas to 0.1 or lower for adult bluefin tuna. Several generalizations, beginning with Gulland, have examined the possibility of defining the MSY reference point in terms of natural mortality rate and biomass. Gulland (1971) proposed that M is approximately equal to M at MSY and hence, for the logistic model,

$$MSY = 0.5*M*B_0 \qquad (1)$$

Several authors have since questioned this equation, (e.g. Garcia *et al.*, 1989) and hence there is also a concern that F (MSY) = P*M, for P = 1 would be too optimistic as a means of guessing at the order of magnitude for a safe fishing mortality corresponding to MSY, especially for short-lived animals. In general, various authors suggested that P should be lower for shorter-lived species. Patterson (1992) proposed for small pelagics that a value of P = 0.5 (F_{MSY} = 0.5M) would be appropriate. Objective data on this point are difficult to find, but one solution proposed here is that P declines linearly with M, so that F(LIM) is smaller relative to M for short-lived than for long-lived species. Based on the preceding account, a linear decline in P with natural mortality rate between two sets of extreme values was postulated, based on the following two data sets:

	Apical predator	Small pelagic fish
M =	0.1	1.25
P =	0.9	0.50

Solving for these values (and admittedly other sets of 'seed' values could have been used), gives the empirical relationship below:

$$F_{LIM} = 0.981M - 0.194\,M^2 \qquad (2)$$

A range of values for F_{LIM} using this approach are given in Table 5.

Table 5. Predicted values for F_{LIM} from equation 2

M	P	F_{LIM}
0.1	0.836	0.084
0.2	0.803	0.161
0.3	0.771	0.231
0.4	0.739	0.296
0.5	0.707	0.353
0.6	0.674	0.405
0.7	0.642	0.449
0.8	0.610	0.488
0.9	0.577	0.520
1	0.545	0.545
1.1	0.513	0.564
1.2	0.480	0.576
1.3	0.448	0.583
1.4	0.416	0.582
1.5	0.384	0.575

It is postulated that an F-based LRP determined in this way (Fig.9) might be tested against other estimators, and could be used to determine a cautious level of target fishing intensity using the methods given in Caddy and McGarvey or the simple exponential relationship given by ICES in Table 2.

A number of variations of equation (1) have been used, e.g. substituting x for 0.5. Annala (1993) notes that in New Zealand, values for

$MCY = 0.25*F_{0.1}*B_0$

have been used in new fisheries to set a conservative TRP, and

$MCY = 0.5.F_{0.1}*B_{av}$

has been used in 'mature' fisheries, both regarded as relatively conservative. The quantity B_{av} in the last equation is the average historic recruited biomass. Simulation results (Mace, 1988) are reported to have shown that MCY may be as low as 60% of the deterministic MSY. Does this make MCY a possible candidate as a TRP to accompany MSY (used as an LRP) in a management system?

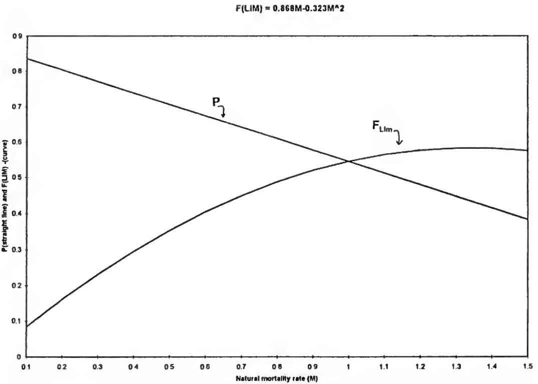


Figure 9. Empirical relationship proposed between natural mortality rate and the limiting value for fishing mortality rate (see text).

FUNCTIONING OF AN LRP-BASED SYSTEM

It is not always clear from the scientific literature how the LRPs specified are expected to be used. Two possibilities seem to be allowed for here, which can perhaps be referred to as 'targeted' or 'non-targeted'.

1. In the first case, a TRP is still specified, and the fishery is managed so as to try and hit this target, with the proviso that, from precautionary considerations, statistical analyses and modelling are aimed at ensuring that the possibility of overshoots is minimized.

   In an earlier paper (Caddy and McGarvey, 1996), the strategy was proposed of setting the LRP first, based on, for example, known MSY conditions or biological fundamentals. A TRP is then estimated as a secondary quantity, based on the degree of uncertainty in the position of the fishery so that a degree of guesswork may be needed, and an acceptable probability of overshoot is agreed to by management. It is recognized that estimating variance is often problematical for control variables such as fishing mortality.

   This admittedly approximate approach can allow a rapid solution for the TRP using a hand calculator and the formula in the Appendix from Caddy and McGarvey (1996) can be used if a normal distribution of error is believed to be a reasonable approximation. Alternatively, a mathematical package such as MAPLE gives solutions for a lognormal distribution of error around F_{NOW}, the current best estimate of fishing mortality on the stock, using other formulations reported by the above authors. The authors note that the normal distribution, though theoretically less acceptable, gives very similar results if the acceptable probability of overshoot is of 10-15% or more (which seems reasonable in practice, otherwise the fishery would have to be run at very low levels of target yield), making this approach a relatively simple way of obtaining an approximate solution for the TRP, given an LRP.

2. A 'non-targeted' or 'feedback-control' approach is, in theory, possible, whereby the fishery is allowed to operate at the economically optimal level of effort with no specific stock assessment target defined. This conclusion is subject to the proviso that, on triggering one or more LRPs, the fishing effort is then reduced significantly the following season. The level of drop in effort or quota must then be sufficient and of sufficient duration to ensure that the resource has a chance to recover to a level above that which applied before the management correction was imposed. In two recent papers (Caddy, 1998, and Caddy, in press), the idea was floated of a possible participatory approach to LRP management, using several LRPs in a 'traffic-light' control rule. This resembles theoretically fuzzy-logic controllers in smoothed feed-back systems. A variable response is implied such as that the severity of management correction increases as the number of LRPs turn from 'green' to 'red' on a 'management board' (similar to the public notice boards used for fire risk warnings in forests) (Fig.10).

   In the 'non-targeted' approaches (and probably in the targeted ones also, given that it is difficult to allow for regime shifts that change production levels over decadal and longer scales), the fishery is likely to go through a series of oscillations (see hypothetical example in Figure 11). This example also illustrates that corrections may needed to be applied over a series of years before a negative resource trend is reversed, and this makes such a management system always incipiently similar to a stock recovery strategy. Such oscillations may be more marked, if there are delays in applying controls before inevitably more severe management reactions to declining harvests are imposed by necessity. In such cases, the oscillations are due to 'runaway' overshoots in effort (or declines in spawning biomass), as opposed to undetected regime shifts which change recruitment and/or the effective fishing power (due to changes in aggregation patterns). What will also be required is to recognize that such an oscillatory system is probably inevitable. We should also note (as for stock recovery strategies) that corrective action should continue to be applied until a markedly higher biomass is reached than when they were initiated, otherwise the fishery risks becoming 'stuck' at close to the LRP level.

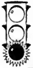
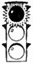
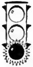
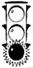
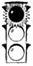
LRPs	STOCK "TRAFFIC" LIGHT	PRECAUTIONARY "TRAFFIC" LIGHT	
		# red lights ?	Management Response ?
$Z \leq Z^{*}$?		5	FISHERY CLOSURE ! (until at least 3? 4? lights are green again!)
$B \leq 0.2B_{0}$?		4	QUOTA/EFFORT not to exceed 0.20 * $\left\{\begin{array}{l}\text{MSY}\\ f\text{MSY}\end{array}\right.$
$F \leq xM$?		3	QUOTA/EFFORT not to exceed 0.40 * $\left\{\begin{array}{l}\text{MSY}\\ f\text{MSY}\end{array}\right.$
$R_{l\text{-}m,l} > \bar{R}$?		2	QUOTA/EFFORT not to exceed 0.60 * $\left\{\begin{array}{l}\text{MSY}\\ f\text{MSY}\end{array}\right.$
$F > \left\{\begin{array}{l}{}^{2}\!/_{3}F_{MSY}\ ?\\ F_{0.1}\ ?\end{array}\right.$		1	QUOTA/EFFORT not to exceed 0.75 * $\left\{\begin{array}{l}\text{MSY}\\ f\text{MSY}\end{array}\right.$

Figure 10. Using a 'basket' of LRPs to judge a fishery (*left*) based on the net change in a series of 'traffic lights' from green (bottom light) to red (top light) as the LRPs are infringed. The number of red lights lit dictates the severity of the management response (*right*), which continues until the red lights turn green again.

SPECIFIC PROBLEMS AND APPROACHES FOR TUNA FISHERIES

It becomes very clear from analysis of fisheries landings (e.g. Caddy and Gulland, 1983; Spencer and Collie, 1997) that fisheries are very dynamic and that recruitment, and hence biomass, react in a sensitive way to environmental changes and fishery impacts. Some oscillations in production are therefore probably inevitable for most fisheries. A fishery management system that is aimed at harvesting a stable yield year after year will probably have to reduce target mortalities to below $F_{0.1}$, or even lower. In this respect, fisheries for oceanic resources such as tunas may have some advantages in relation to shelf demersal fisheries. This follows from the nature of the fishing process; considerable expenditures of effort, capital and time necessary for offshore operation may make it difficult in open ocean areas for most resource populations to be driven to very low levels without uneconomic expenditures of time and effort. This would suggest that fisheries economics, as well as simple biological criteria, could provide a starting point for the search for RP's, such as f_{MEY}, the fishing effort corresponding to Maximum Economic Yield.

Empirical criteria could be useful here and may even be framed in terms of a series of arbitrary ratios, agreed minima for which might trigger a reduction in harvesting intensity. Some ideas here (especially in the case of fisheries with observer systems or satellite surveillance systems) might be to set minima for one or other of the following ratios:

(1) School sightings/Distance steamed on the fishing grounds

(2) Number of sets/Distance steamed on the fishing grounds

or expressed in energetic terms:

(3) (Tons harvested/ton fuel consumed)

or based on easily available catch statistics, e.g.:

(4) % mature fish in the catch

(5) [mean size in the catch)/[size at 50% maturity]

Any of these indices (or all in combination, see later) might be expected to decline as the stock declines in abundance, and any of them could be used to decide on limiting values that could lead to a reduction in fishing effort until the index in question has shown signs of a return to 'normal' conditions. Determining biomasses for oceanic and most developing country fisheries also poses significant problems. These quantities may only be derived indirectly or under certain assumptions from production model or other analyses, hence indices such as the above may be reasonable proxies for abundance.

The question of 'cryptic biomass' (e.g. Fonteneau and Soubrier, 1996) has been raised, which implies that only a fraction of the tuna biomass is available in accessible areas at attractive densities to support a fishery. This 'refugium' concept in fact provides a useful management buffer but also makes biomass-based indices or CPUE somewhat doubtful as indices of total abundance, though these may be relevant indices for local stock size.

REFERENCE POINTS FROM SIZE-AND-AGE DATA?

In absence of systematic age reading of, for instance, otoliths, size frequency data may be used to estimate age compositions as a base for VPA or other procedures. In practice, however, this is not extensively done for most oceanic or developing country species or for most invertebrates. It may nonetheless be possible to use catch size composition and growth curves determined from biological sampling or tagging to gain rough estimates of total mortality at age and age/size at maturity. Various common criteria have been proposed for estimating mortality from size compositions (e.g. Sparre *et al.*, 1989) which will not be entered into here, but Die and Caddy (1997) note that combining mortality estimates with size at maturity leads to an LRP criterion in terms of a Z-based LRP, Z^*, defined by the inequality or limit:

$Z^* < K(L_{inf} - L_m)/(L_m - L_c)$

where L_m is the mean age at maturity. This inequality seeks to establish a limit in terms of conditions whereby a 50% chance of spawning at least once in the life history is assured, with the implication that, if not respected, due precaution is not being exerted.

The plot of total production against total mortality also yields a useful TRP, the point of Maximal Biological Production, which Die and Caddy (1997) show to be a relatively conservative TRP that corresponds to somewhat lower levels of fishing mortality than at MSY.

DIAGNOSIS OF AREAS WHERE LRPs ARE REQUIRED

A diagnostic approach was proposed to NAFO for those stocks where it has been difficult so far to quantify reference points due to lack of information (Caddy, 1998). This questionnaire or 'traffic-light' approach places fisheries in 'red', 'orange' or 'green' categories according to easily assessed, non- or semi-quantitative multiple criteria, and appears to provide some assistance in deciding where priority should be given in the application of a precautionary approach.

MULTISPECIES RPs?

Both ICES and NAFO have had difficulties in deciding on how to set RPs in multispecies fisheries, and this is a major problem, given the multispecies nature of most of their fisheries. Some conclusions seem to emerge from this process, however:

> Multispecies reference points which take into account impacts of the fishery not only on the target species but on its by catch-species, predators, prey and competitors, would normally have to be more conservative than if the target stock is considered alone. This is not only because there is a need under the Biodiversity Convention and UN Agreement to maintain self-sustaining stocks of all species concerned (including incidental captures) but because some of them (e.g. dolphins) probably require lower RPs in terms of fishing mortality than the target species. For most oceanic tunas, the prey species are rarely heavily exploited and predators are not well defined, so this problem seems somewhat simpler than for demersal fish assemblages, a situation that is far from the case for shelf fisheries.

Comparable considerations would seem to apply for shelf fisheries, and multi-species RPs could be derived from ecological/food web models.

SPATIAL INFORMATION AND REFERENCE POINTS

Migration or mixing of stocks may make it difficult to decide what population units we are dealing with. So far, fisheries reference points seem to have been expressed largely in terms of biomass or fishing mortality. Tag and recapture methods may be one of the few feasible ways of estimating mortality more or less directly, despite the time and cost involved, and some progress has been made in this area. It remains to be considered whether it is feasible economically to run continuous tagging activities as a means of estimating mortalities. A number of other possibilities remain that may be more feasible in the case of fisheries where relatively detailed spatial information is available. Several options seem worth exploring here:

1. It is assumed that following the start of a fishery, several stages may occur as progress is made from unfished to overfished conditions, and that this transition that might be picked up by a simple spatial index of aggregation for $i = 1,2,3...N$ unit areas, such as that proposed by Gulland (1955).

   $I_g = [\mathrm{Sum}\ (C_i) / \mathrm{Sum}\ (f_i)] / [\mathrm{Sum}\ (cpue_i) / N]$

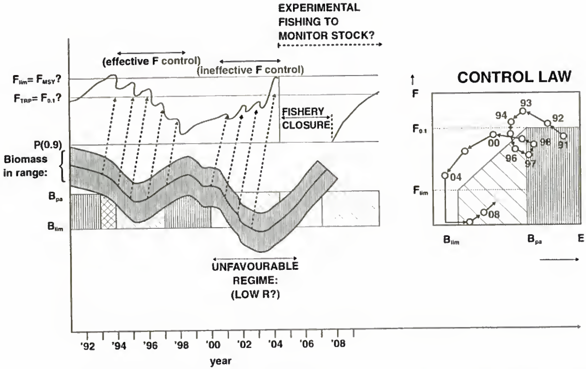


Figure 11. Preconceptions of some aspects of the likely functioning of a fishary control law (*right*) suggesting that, given variances in biomass estimates and variable enforcement of mortality rates, under- or over-compensation by effort corrections seems inevitable, leading to oscillations around the control law.

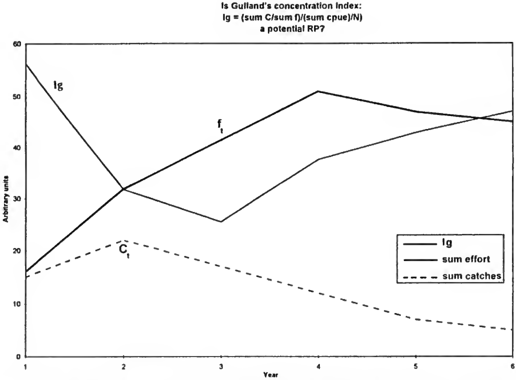


Figure 12. Some manual calculations for a hypothetical data set corresponding to the sequence of events 1(a) to 1(d) in the text that suggest that Gulland's concentration index (1955) may be worth investigating as the basis for an RP for tuna fisheries.

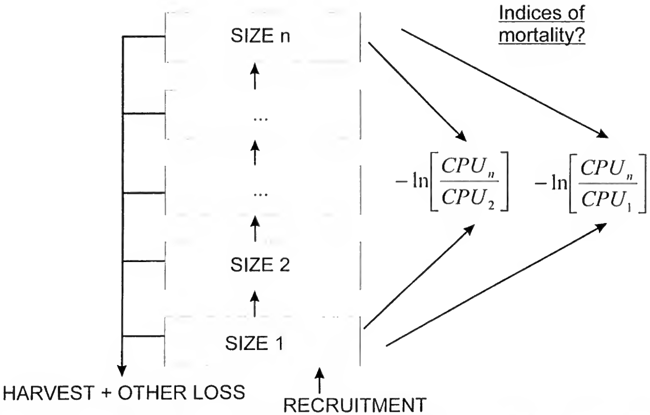

Indices of mortality?
SIZE n
...
...
SIZE 2
SIZE 1
$-\ln\left[\frac{CPU_n}{CPU_2}\right]$
$-\ln\left[\frac{CPU_n}{CPU_1}\right]$
HARVEST + OTHER LOSS
RECRUITMENT

Figure 13. Some possible indices of mortality for a migrating cohort which is fished in a gauntlet fashion in successive locations along a migration route. The ratios may be used both for allocation and possibly limiting values of them could be considered as RPs (modified from Kleiber, 1996).

If this is the case, simple indices of concentration could be used to formulate LRPs designed to pick up unfavourable changes. The results of simulations might be used to specify situations where CPUE becomes low and uniform or where the area fished contracts in size with over-exploitation. The following stages might perhaps be looked for in sequence:

(a) Relatively few areas are fished, with initially high CPUE and relatively low effort.
(b) The number of areas fished increases, effort increases, and mean CPUE drops.
(c) CPUE declines and becomes more uniform with further area expansion.
(d) As fishing intensity increases further, CPUE drops again and 'key areas' are 'fished out', with possible secondary areas of concentration of the fishery arising.

Figure 12 shows results of a simplistic hand-calculation designed to reproduce changes (a) to (d) and indicates that I_g may be sensitive to both changes in total area exploited and increased uniformity and decline in subregional CPUEs. It suggests that Gulland's or some similar index could be developed through simulation that could measure over-exploitation as it would show up in a spatially inhomogeneous and mobile population such as for tunas. These possible zoogeographical indicators of over-exploitation could be testable by a model of the type mentioned by Angenuzzi (1996) and could lead to some useful empirical indices of trouble on the horizon, i.e. when a geographical index based on correlation between effort and resulting CPUE suggests that the fishery is approaching stages (c) or (d) above.

2. Another option may be to use one or other variants of the mechanism of fisheries closures as an approach to setting precautionary management criteria. In this case, the proportion of the fishing grounds closed as ecological reserves might be regarded as a reference point whose effectiveness would have to be determined through a knowledge of the order of magnitude of migration or dispersal rates between unit areas. Such closure proportions used as LRPs might be determined by a combination of tagging experiments and dispersion models (Fig.13).

3. A third possibility may be to dictate the level of fishing effort that may be exerted in biologically important individual unit areas in any given season such that local depletion is not achieved, especially where these area/season units are believed to be important for reproduction.

ROTATING CLOSURES AND GAUNTLET MODELS

4. Another approach would be to look at the possibility of rotating harvest regimes such as have been described for territorial or sedentary resources (see Caddy and Seijo, 1998). Here, a constant proportion of all productive unit areas are closed in a given year. Simply for illustration, Table 6 shows the results of several simulations where spatially 'patchy' non-migratory resources are subject to rotations of different duration. The optimum rotation cycle (years) is based on a number of factors, notably the maximum yield, for each of six combinations of the von Bertalanffy K and natural mortality rate M that might apply to a population, and the conclusion reached is that rotation periods longer than six years may be suboptimal in situations where recruit distribution is very patchy:

Table 6. Some close to optimal (integer year) rotation periods (years) for non-migratory resources (from Caddy and Seijo, 1998)

K \ M	0.1	0.3	0.6
0.1	6	6	6
0.3	6	6	6
0.6	4	2	2

Naturally, dispersion will reduce the effectiveness of protection offered by rotating closures, and the simulations done here would have to be repeated with feasible levels of interchange of individuals.

Although apparently less 'water tight' as a mechanism than for non-migratory species, some areas of seasonally high aggregation may be sufficiently protected by a rotating/closure mechanism to ensure spawning occurs undisturbed. Evidently the importance of dispersal between unit areas will depend on the size of these areas in relation to the mean annual dispersal distance of fish, a factor that could be analysed by simulation, in combination with tagging experiments to test various migratory hypotheses.

More relevant perhaps for migratory species is the idea of using the 'gauntlet model' of sequential risk at spatially-differentiated fishing sites to determine acceptable levels of survival to maturity. An index such as that shown in Figure 13, modified from the SPARCLE model presented by Kleiber (1996), could provide some indication of how mortality is fluctuating through time, even if an accurate growth curve may not exist for the species.

Figure 13 modified from the above author suggests that, if a gauntlet model applies and has been confirmed by tagging, and there are fishing sites 1,2,3...n distributed along a known migration route, log ratios of catch rates for a cohort t could be calculated for each fishing season whose values might be adjusted by effort or catch control at each location so as to remain above a certain limit, such that:

$[\ln(CPUE)_{t+DT,n} / \ln(CPUE)_{t,1}] > = R_{crit}$

A general comment applies to all of the above hypothetical management mechanisms based on spatial criteria: they may become more widely used as telemetry systems for locating vessels make oceanic MCS procedures more feasible.

DISCUSSION

This paper ends with a plea for empiricism in setting reference points in conditions of uncertainty and calls for a recognition that LRPs are only components of a management system, and the key criterion that will lead to functionality is acceptance by industry and management. There is a need to test these approaches both in simulation and in practice in order to detect and overcome possible problems of practical implementation of control laws and determine their stability of performance under a range of environmental conditions. The standard approach of seeking to define a management control rule or law obviously is relevant here, but it is not excluded that reliance may also have to be placed on empirical measures. Using a 'basket' of empirical measures, each derived from fundamentally different data sources in a 'traffic-light' mode, may provide a good indicator of the need for management action, just as, in another sphere, the Dow-Jones index of the New York Stock Exchange provides a sensitive indicator to performance of the whole market based on the performance of a small number of key stocks. Once a degree of confidence has been established as to the performance of such multiple criteria, they may be incorporated into the fishery management scheme as one way of achieving a flexible response to changing conditions.

Obviously there are some serious difficulties in reproducing many of the S-R based reference points favoured in the ICES/NAFO area for stocks where long series of recruits and/or age structure are not available. At the same time, fisheries often offer considerable level of detail in catch statistics by subarea (see, for example, Carocci and Majkowski, 1996), which could provide the basis for novel indicators of over-exploitation such as have only been hinted at in this paper. For tunas, these would require further information on migration and could be tested by a combination of simulation and detailed tagging data.

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ALTERNATIVE CLOSED-FORM SOLUTION FOR F_{NOW}

The following formula (Abramowitz and Stegun, 1970, equation 26.2.23) provides a closed-form approximation solution, accurate for four significant digits, for F_{NOW}:

$$F_{NOW} = \frac{F_{MSY}}{1 + CV_F\left(t - \dfrac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right)},$$

where

$$t = \sqrt{\log_e\left\{\frac{1}{[P(F > F_{MSY})]^2}\right\}},$$

and $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

This paper summarizes the recent development and use of reference points for fisheries management and their current contribution to precautionary fisheries management. Reference points are only relevant in the management context if they are incorporated into harvest control laws which form the basis for management action. They need to be reconciled through discussion and negotiation among managers, fishers and the fishing industry, since the risk that a particular fishing strategy will be precautionary depends on the overall performance of the fishery as a system and not just on the precision of the reference point. Reference points are only one component of a precautionary management system; precisely formulated reference points as part of a fisheries control law will be ineffectual in the absence of industry's agreement to act when the limit reference points are approached or exceeded or in the absence of prompt and effective surveillance to detect infringements. The review looks mainly at reference points that could be of particular use for developing countries' fisheries and shellfish resources or for oceanic resources such as tuna, where conventional approaches used in north-boreal shelf fisheries may not be applicable because of lack of data on age structure and recruitment. Consideration of the use of multiple reference points based on different criteria is suggested. Where data is scarce, precaution is even more necessary, but reference points may have to be partly empirical. Emphasis is placed on describing a number of options to be explored further through simulation and later through practical trials. Attention is given to different ways in which reference points could be combined in control laws within a fisheries management system.

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